

Globular Clusters as Testbeds for Type Ia Supernovae

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ABSTRACT

Fundamental mysteries remain regarding the physics of Type Ia supernovae (SNIa) and their stellar progenitors. We argue here that important clues to these questions may emerge by the identification of those SNIa that occur in extragalactic globular clusters—stellar systems with well defined ages and metallicities. We estimate an all-sky rate of $\approx 0.1\eta(D/100 \text{ Mpc})^3 \text{ yr}^{-1}$ for SNIa in globular clusters within a distance D , where η is the rate enhancement per unit mass as a result of dynamical production channels that are inaccessible in the galactic field. If $\eta \approx 2 - 10$, as suggested by observations and theory, the combined efforts of accurate supernova astrometry and deep follow-up imaging should identify the $\gtrsim 1\%$ of nearby ($D < 100 \text{ Mpc}$) SNIa that occur in globular clusters.

Subject headings: galaxies: general — globular clusters: general — supernovae: general

1. Introduction

Many questions remain about the most fundamental aspects of Type Ia supernovae (SNIa), including the triggering and hydrodynamics of the explosions (e.g., Hillebrandt & Niemeyer 2000), and the nature of their stellar progenitors (e.g., Yungelson 2005). The increasing SNIa diversity, with some very bright (e.g., Howell et al. 2006), some very faint (e.g., Kasliwal et al. 2008), and some that do not follow the Phillips (1993) relation (e.g., Jha et al. 2006) has energized the discussion of many possible formation scenarios.

While at most a few percent of white dwarfs explode as SNIa (Pritchett et al. 2008), there are only loose constraints on the specific binary evolution pathways (e.g., Iben & Tutukov 1984; Yungelson 2005). There is a consensus that SNe Ia originate from thermonuclear ignition and burning of a C/O white dwarf in a binary system. Yet it remains uncertain if the event is triggered by accretion from a hydrogen-rich companion or from a merger with another white dwarf (see Branch et al. 1995), referred to as the single-degenerate and double-degenerate scenarios, respectively. In the single-degenerate scenario, the main issues are the nature of the companion, and

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if mass transfer can be sustained onto the white dwarf at the favorable rate in a sufficient number of systems to match the observed SNIa rate (Maoz 2008). In the double-degenerate scenario the primary issue is whether off-center carbon ignition can be avoided, as this would transform the C/O white dwarf into a O/Ne/Mg white dwarf (e.g., Nomoto & Iben 1985) rather than generate a SNIa (see however Regos et al. 2003).

In fact evidence is amassing that multiple progenitor scenarios lead to SNIa. In particular, there is a clear disparity in the SNIa rates in late-type galaxies with active star formation and elliptical galaxies that contain mostly old (5–10 Gyr) stars (Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006). This suggests that $10^8 - 10^{10}$ yr can elapse between the birth of the progenitors and the explosions, a challenge for any single progenitor scenario (Della Valle & Livio 1994; Mannucci et al. 2006). Multiple routes to SNIa may well lead to diversity in the explosive outcomes. For example, low-luminosity SNIa are most prevalent in early-type (i.e., E/S0) galaxies, while the most luminous events occur only in star-forming galaxies (e.g., Hamuy et al. 1996).

We propose that the study of SNIa in globular clusters (hereafter, GC Ia) may provide unique clues to understanding SNIa. Although globular clusters (GCs) and elliptical galaxies are both composed mainly of old stars, there are crucial differences between them. In a given GC, we are certain that all stars were born within 1 Gyr of each other, whereas elliptical galaxies often show evidence for a substantial spread of stellar ages (e.g., Trager et al. 2000). Secondly, in an individual GC, the stellar metallicities are narrowly distributed, and thus the integrated metallicity is a good measure of the metallicity of any of the constituent stars. Until recently, there was only one known exception (ω Cen) in the Milky Way (Freeman & Rodgers 1975; Bedin et al. 2004), but more recent work has found that a few massive ($> 10^6 M_\odot$) GCs have helium-rich sub populations (e.g., Piotto 2008). In any instance, GCs have metallicities low enough that a single GC Ia detection would place strong constraint on theoretical models (Kobayashi et al. 1998; Hachisu et al. 1999; Piro & Bildsten 2008).

GCs are differentiated from the galactic field by their high stellar densities (often $\gtrsim 10^5 M_\odot \text{ pc}^{-3}$) that trigger frequent close encounters between stars and binaries. Such encounters are responsible for the high incidence of exotic objects in GCs, including X-ray binaries, rapidly spinning radio pulsars, blue stragglers and cataclysmic variables (e.g., Hut et al. 1992; Sills et al. 1999; Rasio et al. 2000; Pooley & Hut 2006). Dynamics will almost certainly play an important role in the production of GC Ia progenitors (Shara & Hurley 2002; Ivanova et al. 2006; Rosswog et al. 2008), likely increasing the GC Ia rate per unit mass.

We start in §2 by estimating the GC Ia rate and discussing the possible dynamical enhancements. The observational challenges to finding a GC Ia are discussed in §3, where we motivate that the maximum distance for such a search is 100 Mpc. We also explain the need for accurate astrometry of nearby SNe that will enable meaningful followup observations. We close in §4 by describing the implications of detecting even a single GC Ia.

2. The Supernova Rate in Globular Clusters

Globular clusters (GCs) have $\sim 10^5$ – 10^6 old (> 8 Gyr) stars inside a few parsecs, with a wide range of $\lesssim 0.3Z_\odot$ metallicities. All galaxies contain GCs, with total numbers scaling as ~ 100 GCs per $10^{10} L_\odot$ (Ashman & Zepf 1998). The common measure of the GC number density is the V -band specific frequency,

$$S_N = N_{\text{GC}} 10^{0.4(\mathcal{M}_V + 15)} , \quad (1)$$

where N_{GC} is the number of GCs, and \mathcal{M}_V is the absolute V -band magnitude of the galaxy (Harris & van den Bergh 1981). Typical values of S_N are $\simeq 1$ for spiral galaxies and $\simeq 2$ – 5 for ellipticals (Harris 1991). Though standard, S_N is not the best choice for our purposes. We are most interested in the fraction of stellar mass in GCs, $F_{\text{GC}} = M_{\text{GC}}/M_g$, where M_{GC} is the total mass of the GC system and M_g is the total stellar mass of the galaxy. Given the galactic stellar mass-to-light ratio Υ_V , F_{GC} is related to S_N by

$$F_{\text{GC}} = 1.2 \times 10^{-3} S_N m_5 \Upsilon_V^{-1} , \quad (2)$$

where m_5 is the mean GC mass in units of $10^5 M_\odot$, and we use $\mathcal{M}_{V,\odot} = 4.8$ for the absolute magnitude of the Sun. Photometric studies of GC systems find $m_5 \simeq 2$, and old elliptical galaxies have $\Upsilon_V = 3$, so that $F_{\text{GC}} \approx 2 \times 10^{-3}$ for most ellipticals, while it is somewhat less for spirals. For some central dominant ellipticals at the centers of galaxy clusters, S_N can reach 10 (Harris et al. 2009), corresponding to $F_{\text{GC}} \approx 10^{-2}$.

Scannapieco & Bildsten (2005) and Mannucci et al. (2005) proposed that the SN Ia rate in a galaxy is the sum of two components, one proportional to the total stellar mass M_g , the other proportional to the star formation rate \dot{M}_g . Such a model suggests that SNIa result from at least two evolutionary channels. For a particular galaxy, the two-component rate can be written as

$$\text{SNR}(t) = A M_g(t) + B \dot{M}_g(t) , \quad (3)$$

where A and B are constants. Using a well characterized sample of SNIa and host galaxies, Sullivan et al. (2006) find basic agreement with eq. (3) and determine $A = (5.3 \pm 1.1) \times 10^{-14} \text{ yr}^{-1} M_\odot^{-1}$ and $B = (3.9 \pm 0.7) \times 10^{-4} \text{ yr}^{-1} (M_\odot \text{ yr}^{-1})^{-1}$.

The value of A is derived from SNIas in E/S0 galaxies with no discernible star formation (i.e., $B = 0$). If these galaxies are truly old, with negligible star formation in the past ≈ 5 – 10 Gyr, then a reasonable first guess is that the same rate per unit mass also applies to GCs (the enhancement due to stellar dynamics is discussed below). Adopting the galactic value of A for GCs, the GC Ia rate in a galaxy is $A M_g F_{\text{GC}}$. An estimate of the local cosmic rate density of GC Ias is obtained as follows.

At low redshift, the total K -band luminosity density is $j_K \simeq (5 \pm 0.5) \times 10^8 L_{\odot K} \text{ Mpc}^{-3}$ ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Kochanek et al. 2001) and the fraction in E/S0 galaxies is 40–50%. Given

the mean K -band stellar mass-to-light ratio $\Upsilon_K \approx 1$, the contribution to the Ia rate density from old stellar populations is $Aj_K \Upsilon_K$. Here we let $\Upsilon_K = 1 \pm 0.5$, averaged over all galaxy morphological types, where the uncertainty largely reflects a range of model assumptions, rather than measurement error (e.g., Cole et al. 2001). We find $Aj_K \Upsilon_K \approx (2.7 \pm 1.5) \times 10^{-5} \text{ yr}^{-1} \text{ Mpc}^{-3}$. This is consistent with the recent measurement at $z \approx 0.1$ (Dilday et al. 2008), showing the dominance of the old stellar population for the local SNIa rate. The corresponding GC Ia rate density is then $Aj_K \Upsilon_K \langle F_{GC} \rangle$, where $\langle F_{GC} \rangle$ is the mean GC mass fraction over a large number of galaxies. If we adopt a plausible value of $\langle F_{GC} \rangle = 10^{-3}$ (see eq. [2]), we estimate a

$$\text{GC rate from mass alone} \approx 3 \times 10^{-8} \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (4)$$

Under our given assumptions, we expect that the net uncertainty in this rate is a factor of ≈ 2 .

However, it has been known for over 30 years that X-ray binaries are $\gtrsim 100$ times more abundant per unit mass in GCs than in the disk (Clark 1975; Katz 1975). Dynamical interactions involving single stars and binaries occur frequently in GCs and naturally account for this overabundance (e.g., Bildsten & Deloye 2004). There are also excellent observational and theoretical arguments that dynamics shapes the GC populations of blue stragglers, millisecond pulsars, and cataclysmic variables (e.g., Sills et al. 1999; Rasio et al. 2000; Pooley & Hut 2006).

Recently, Shara & Hurley (2002) and Ivanova et al. (2006) explored the idea that SNIa progenitors can be formed by dynamical means in dense star clusters, leading to a mean enhancement of the GC Ia rate per unit mass, η . Shara & Hurley (2002) suggest that the number of WD-nondegenerate star binaries is similar in dense clusters relative to the field, although they found strong differences in the masses of the companion stars, which could be important in determining which binaries support stable accretion. The models described in Ivanova et al. (2006) suggest an enhancement of $\eta \approx 1\text{--}7$ for single-degenerate progenitors, where the range in η reflects variation with metallicity and other parameters.

In the double-degenerate case, Shara & Hurley (2002) showed that supra-Chandrasekhar WD-WD merger rate is over an order of magnitude higher in dense clusters than in the field. On the other hand, Ivanova et al. (2006) suggest a more modest enhancement of $\eta \approx 2$. Based on recent studies of the prevalence of post classical novae supersoft sources in M31 GCs, Henze et al (2008) conclude that the nova rate in GCs may be as much as ten times higher than in an old field stellar population, and they suggest that GC Ia may be detectable in future surveys. Overall, it seems conceivable that $\eta \approx 1\text{--}10$ and that observed GC Ia may help differentiate progenitors.

3. Observational Considerations within 100 Mpc

The maximum distance of interest is set by the need to find the underlying GC. GCs have a distribution of absolute magnitudes given by $dN/dM_V \propto \exp[-(M_V - M_{V,0})^2/2\sigma_V^2]$, where the dispersion is $\sigma_V \simeq 1\text{--}1.5$ in relatively bright galaxies with $M_{V,\text{gal}} < -20$. Over a wide range of host

galaxy properties, the mean is $M_{V,0} = -7.4$ to within a few percent (e.g., Harris 1991; Jordán et al. 2007) and has been detected at the 100 Mpc distance of the Coma cluster, where the turnover apparent magnitude ($\simeq 27.6$) is accessible by the *Hubble Space Telescope* (Harris et al. 2009). Observations from the ground are presently limited to magnitudes of $m_V \lesssim 26$, corresponding to the GC luminosity function turnover at distances of $\lesssim 50$ Mpc.

For a given limiting apparent magnitude V_{\max} , the fraction of stellar mass in GCs brighter than V_{\max} is

$$f(V < V_{\max}) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{(V_{\max} - \widetilde{M}_V)/\sqrt{2\sigma_V^2}} dx e^{-x^2}, \quad (5)$$

where $\widetilde{M}_V = M_{V,0} + \text{DM} - 0.4(\ln 10)\sigma_V^2$, and DM is the distance modulus. When DM = 35 and $V_{\max} = 26$, as σ_V increases from 1 to 1.5, f increases from 0.25 to 0.62, while the fraction of globulars with $V < V_{\max}$ varies from 0.05 to 0.14. Even though the fraction of visible clusters may be small, the fraction of stellar mass contained within these clusters can be substantial, and typically exceeds 50% when DM < 35 and σ_V takes its usual values of $\simeq 1.3$ – 1.5 . Hence, observations of a galaxy at 100 Mpc for which the GC census is complete for clusters brighter than $V = 26$ finds $\simeq 15\%$ of the globulars by number but $\simeq 60\%$ of the stellar mass. This is an important point, since a dynamical enhancement in the GC Ia rate may favor more massive clusters, making it of considerable interest to pursue GC Ia within DM = 35 (Pooley & Hut 2006). At distances greater than ≈ 100 Mpc, it becomes extremely difficult to identify a significant number of GCs, and those detected in the outskirts of the galaxy will represent only a small fraction of the mass of the GC system.

From eq. (4) and our discussion of the dynamical enhancement of the GC Ia rate per unit mass, we estimate a local GC Ia rate of $\approx 0.1\eta (D/100 \text{ Mpc})^3 \text{ yr}^{-1}$. A plausible value of $\eta \sim 10$ results in ≈ 1 GC Ia per year within 100 Mpc, which is about 1% of the total SNIa rate within 100 Mpc. What are the prospects for carrying out such a search? The typical SNIa within 100 Mpc would have a peak visual magnitude of $m_V \approx 16 - 17$ and even the subluminous, 1991bg-like SNIa would be found at these distances in the upcoming wide angle (one-tenth of the sky) nearby SNe surveys (e.g., Palomar Transient Factory, SkyMapper and Pan-STARRS1). The SNIa yields from these new surveys, as well as the increasing numbers from targeted galaxy and cluster searches by LOSS-KAIT, CHASE, and ROTSE, makes the time right for explicit GC identification efforts. In some cases, prior HST or ground-based studies will have GC catalogs to cross-list locations. However, the typical case will require waiting until the SNIa has faded below the GC light.

The few well-studied late-time SNIa light curves reach $M_V \approx -7$ after ≈ 600 days (e.g., Sollerman et al. 2004; Lair et al. 2006), at which point their fade rates are 1.4 magnitudes per 100 days in BVR (Sollerman et al. 2004) with colors of $V - R \approx -1$ and $B - V \approx 0$, much bluer than a GC. The I band decays more slowly (≈ 1 mag in 100 days), again pointing to BVR for discovery. One possible way to first discern the presence of an underlying GC would be the detection of a modified BVR color evolution as the redder BVR colors of the GC ($V - R \approx 0.4$ – 1) begin to shine through.

After identifying a candidate GC Ia, high angular resolution observations are required: (1) to confirm that the SNIa and GC lie along the same sightline, and (2) to minimize the likelihood that the SNIa occurred in the host galactic field, in front or behind the GC. If the GC and SNIa are found to overlap within a resolution element of diameter θ (in arcsec) the probability that the SNIa occurred in the field is roughly $L_\theta/L_{GC} \equiv \epsilon$, where L_{GC} is the GC luminosity and L_θ is the luminosity in field stars within the resolution element. A definitive GC Ia detection requires a small value of ϵ , and a correspondingly small value of L_θ . Since surface brightness, and thus L_θ , generally falls with increasing galactocentric radius, the strongest GC Ia candidates will be located far from the centers of their host galaxies. To illustrate this point more quantitatively, we assume a de Vaucouleurs profile with a surface brightness $\mu_e = 19.5$ mags/arcsec² at the half-light radius, R_e (e.g., Djorgovski & Davis 1987). We further assume that the target GC has magnitude $M = -7.5$ and that the GC is unresolved (the typical GC half-light diameter is $\lesssim 0''.1$ beyond 10 Mpc). With these assumptions, we find that the radius at which $L_\theta/L_{GC} = \epsilon$ is given by

$$\frac{R}{R_e} = \left[\frac{34}{25} + \frac{3}{10} \log \left(\frac{D_{10}^2 \theta^2}{\epsilon} \right) \right]^4, \quad (6)$$

where $D_{10} \equiv D/10$ Mpc. For $\epsilon = 0.1$ and $D_{10} = \sqrt{10}$ ($\simeq 31.6$ Mpc) we find $R/R_e \simeq 3.4$ when $\theta = 0.1$ arcsec, and $R/R_e \simeq 0.78$ when $\theta = 0.02$ arcsec. At a distance of 100 Mpc, the same two θ values give $R/R_e \simeq 7.6$ and $\simeq 2.3$. However, at 1.0 arcsec resolution, $R/R_e \simeq 14.7$ even when $D_{10} = \sqrt{10}$. Since typical half-light radii are $R_e = 1\text{--}4$ kpc, it is clear that $\lesssim 0''.1$ resolution is required to achieve modest R for small ϵ , which can only be accomplished from space or with ground-based adaptive optics. Even then, the best GC Ia candidates will be at $R > 10$ kpc, which requires accurate astrometry of both the active SNe and the possible underlying GC. These limits highlight the value of extremely accurate astrometry for making GC Ia measurements in the future with large ground-based telescopes.

4. Implications of a Discovery

A major open question is how a 10 Gyr old stellar population produces an appreciable SNIa rate, as this requires double-degenerate mergers or stable accretion from relatively low-mass donors, neither of which are currently-favored for SNIa production. While some elliptical galaxies show definite signatures of relatively recent low-level star formation within an otherwise very old system (e.g., Trager et al. 2000), we can be confident that no new stars are forming in old GCs. A single, definitive GC Ia detection would demonstrate that, in fact, SNIa do occur in truly old stellar systems.

Secondly, any systematic trends in GC Ia properties with metallicity contain information about the physics of the explosions. GCs are, with few exceptions, extremely uniform in their chemical compositions, and the same cannot be said of elliptical galaxies (e.g., Mehlert et al. 2003). Of course, the metallicity can vary a great deal between GCs, but the metallicity of an individual

cluster is readily determined from its photometric colors. The detection of a single $[\text{Fe}/\text{H}] < -1$ GC Ia would place strong constraints on models of stable white-dwarf accretion from a non-degenerate companion (e.g., Kobayashi et al. 1998; Hachisu et al. 1999), and analysis of a handful of GC Ia would strongly constrain models of SNIa lightcurves and pre-explosion simmering (e.g., Timmes et al. 2003; Piro & Bildsten 2008).

A potential complication is that the dense stellar environment of the GC may open up exotic paths to SNIa (e.g., Rosswog et al. 2008). We would hope that such an outcome would be revealed in comparison between the GC Ias and the field SNe, both in rates (e.g., Shara & Hurley 2002; Ivanova et al. 2006) and systematic properties, such as lightcurve shapes. If the rates are sufficiently high, GC Ia may prove decisive in implicating nonstandard Ia progenitors such as double-degenerate mergers.

Because it takes approximately two years for a typical Ia to fade to the luminosity of an average globular cluster, GC Ia will require late-time observations. This is not common practice, although it would require minimal investment of telescope time for the closest supernovae, as the total rate is only $\approx 10 \text{ yr}^{-1}$ within 30 Mpc. Accurate astrometry of these events is also critical to the later GC search. For the moment, we must appeal to the Ia archives. In the Sternberg catalog¹, there are 112 SNIa identified from 2005 to 2007 within $z \leq 0.025$ (7500 km/s). Of these, 34 are hosted by E/S0 galaxies, and 6 in this subset are separated by more than $1'$ from the centers of their hosts. Only careful follow-up observations will tell if the first GC Ia has already been detected.

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